Fuzzy Mathematical Frameworks for Sustainable Development Goals: Multi-Criteria Decision-Making, Uncertainty Modeling, and Optimization

SHORT SYNOPSIS

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by

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Date: 29/03/2025

DECLARATION BY THE SCHOLAR

I hereby declare that the short synopsis entitled **Fuzzy Mathematical Frameworks for Sustainable Development Goals: Multi-Criteria Decision-Making, Uncertainty Modeling and Optimization** is being submitted in partial fulfillment of the requirement for the degree of Doctor of Philosophy in the **Department of Sciences (Mathematics) under the School of Sciences** of Manav Rachna University, Faridabad during the academic year 2024-25.

It is the work that is expected to be carried out under the supervision of **Dr. Ankita Gaur**.

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ABSTRACT

This study uses advanced math to understand how the Sustainable Development Goals (SDGs) are connected. It uses special techniques like fuzzy logic to find out which goals are most important for overall progress and to identify potential conflicts between them. We'll create new methods to simulate how different policies might work and be implemented for the good. Also using techniques like fuzzy C-means clustering to find regions that are similar in how well they're doing with the SDGs.

By combining math with sustainability science, this work provides practical advice on how to improve SDG outcomes. It shows how using fuzzy logic and network analysis can help solve complex global problems. Overall, the study helps create reliable tools for making decisions about sustainable development, which is important for achieving the goals set and highlights how math can help solve sustainability issues with speed and accuracy.

Key words: Fuzzy Logic, Input/output variable, Decision Support system, Fuzzy C-means Variables in Linguistics, Systems of Fuzzy Inference, Managing Uncertainty, sustainability

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Introduction:

A growing world population means that food security is a very important factor to be considered as we struggle to deal with the increasing numbers of people. Yields are a fundamental component when it comes to addressing the needs of the increasingly growing population, a good yield will also help address issues to do with poverty as well as matters affecting the environment [3]. Discrepancies of these elements affect plant growth and overall productivity of crops, especially where the farmers are grappling with natural disasters, unfriendly soils and climatic conditions.

India's demographic transition has a considerable impact on agriculture strategies and food security planning. India's population continues to grow, but at a declining level. The United Nations' medium variant projection shows India overtaking 1.5 billion people at the upper bound of this decade and growing until it reaches a peak of about 1.7 billion people in near future.

This significant increase in population highlights the urgent need to bolster food production to accommodate a growing population. And to reach this goal making improved forecasts of crop yields for staples like wheat, rice, and sorghum will be vital. Conventional agriculture uses harsh chemicals and it has some roadblocks like nutrient abstraction, delayed planting season, and limited use of fertilization and irrigation water making yield forecasts.

This involves significant improvements in crop yield predictions for the main staple crops (e.g. wheat, rice, sorghum). While traditional farming methods usually struggle with uneven nutrient availability, long planting periods, fertilizer and water limitations, and complicated yield estimation, AI can provide more accurate agricultural predictions.

To address the above-mentioned challenges, Information and Communication Technology (ICT) has been integrated into Indian agriculture, leading with the adoption of the modern technologies such as machine learning, cloud computing, and the Internet of Things (IoT). These technologies utilize environmental signals to improve the precision of crop yield prediction models, delivering insights directly to farmers. This includes the use of more sensors to monitor crops and livestock, using drones to survey land and automate machinery for planting and harvesting.

Additionally, fuzzy logic has been helpful in solving agricultural uncertainty. By processing information that can’t be boiled down to true or false, fuzzy logic models provide better, more flexible predictions that take into account conditions such as changing climate patterns, uneven soil fertility and changing moisture levels. The contribution of these technologies to a more resilient and efficient agricultural sector is essential for the food security of the growing population of the country.

Literature Review

1. Fuzzy Logic

In 1965, Lotfi Zadeh introduced fuzzy logic, a system designed to handle vague or unclear data. Unlike traditional binary logic, which deals with variables that are either true or false, fuzzy logic offers a more flexible way of solving problems by using degrees of truth (Zadeh, 1965). The key idea behind fuzzy logic is the use of "fuzzy sets," where elements are not strictly classified as either part of a set or not, but instead can belong to the set to varying degrees. This approach is especially useful for dealing with uncertainty in human reasoning (Ross, 2010). Over time, fuzzy logic has found applications in many areas, including decision-making, control systems and more recently, sustainability issues (Mendel, 2001). Its development has been crucial in expanding its use and influence, moving beyond theoretical concepts and into practical applications.

2. Sustainable Development Goals (SDGs)

The Sustainable Development Goals (SDGs) are a set of 17 interconnected global objectives aimed at achieving a better and more sustainable future for all (United Nations, 2015). These objectives address a number of global issues, including environmental degradation, poverty, inequality and climate change. Because of their interdependence, developments in one field frequently have an impact on developments in other fields. For instance, advancing clean energy (SDG 7) has a direct bearing on addressing climate change (SDG 13) and consequently, economic expansion (SDG8). Although accomplishing these objectives is difficult, we as responsible citizens will make an effort to gather information. In some ways, the current methods rely on deterministic and linear models that fail to account for the uncertainties and complexity of sustainability (Griggs et al. (2013). This has made us go in for more flexible and integrated approaches, such as fuzzy logic so as to get better results to address these challenges.

3. Integration of Fuzzy Logic with SDGs

The integration of fuzzy logic with SDGs has emerged as a promising approach to managing the uncertainties and complexities associated with sustainable development. Fuzzy logic has been shown to help make better decisions in areas related to sustainability. For example, it has been used to help urban planners balance the goals of protecting the environment while promoting economic growth (Ring and Morse, 2008). Another study used fuzzy logic to figure out the best ways to handle climate change by considering different levels of risk and uncertainty (Toloo et al., 2020). These examples

show how fuzzy logic is useful in solving complex problems related to the Sustainable Development Goals (SDGs).

In various industries, fuzzy logic has proven helpful as well. For instance, in managing water resources, it was used to find the most sustainable strategies for using water, considering the uncertainty of future demand and availability. Similarly, fuzzy logic has been applied in the renewable energy sector to create policies that balance cost, effectiveness and environmental impact. These examples highlight how fuzzy logic offers a flexible and thorough way to make decisions, helping achieve the SDGs more effectively.

Key Research Inquiry:

This study is working on creating mathematical tools that use fuzzy logic to help make better decisions about achieving the Sustainable Development Goals (SDGs). It focuses on using fuzzy logic to deal with uncertainty and complexity in real-world problems related to SDGs. The research looks at important issues like how resources are distributed, changes in climate, social and economic factors and sustainable farming practices. It aims to provide useful insights into how decisions can be made to support long-term sustainability. By combining mathematical theories with practical efforts to achieve sustainability, this study wants to help organizations make better decisions and improve their strategies for reaching the SDGs.

Research Objectives:

1. To develop a practical decision-support framework that utilizes fuzzy logic for sustainable development planning, enabling better-informed decision models and optimization algorithms for individuals or systems involved in sustainable development, across regions with diverse challenges.
2. To analyze the interconnections between different SDGs using fuzzy logic to identify synergies and trade-offs in achieving multiple goals simultaneously.
3. To evaluate the effectiveness of fuzzy mathematical models in addressing key SDG challenges, particularly in areas such as poverty alleviation, environmental sustainability and food security.
4. To develop a practical decision-support framework that utilizes fuzzy logic for sustainable development planning, enabling better-informed decisions for governments, organizations and individuals across regions with diverse challenges.

Research Methodology

1. Review

   o Provide a new fuzzy predictive modeling for Poverty Degradation with climate intervention.

   o Recognising the deficit in the current knowledge base and setting a plan for future research

2. Data Collection

   o Fetching real-time data from government sites if needed such as on climatic metrics, productivity, argofoods, social indicators etc. in India. Integration of fuzzy models with GIS for localized agriculture

3. Fuzzy Approach

   o Build the fuzzy inference system to project the interaction between the sustainable goals like climate change, agriculture productivity, food security, poverty rate and more.

   o Fuzzy rules to detect the uncertainty and act according to it.

4. Model Development

   o Develop a fuzzy prediction model with MATLAB for precise results to explore correlation between different variables by computer software like MATLAB and Python.

   o Use existing data to verify accuracy and reliability of the model

5. Results:

   o Simulation models for optimizing resource allocation (water, fertilizers) using fuzzy decision-making.

   o Integration of fuzzy models with geographic information systems (GIS) for localized agricultural planning and policy recommendations.

Mathematical approach:

The rules of inference in fuzzy logic are used to make decisions or draw conclusions based on fuzzy sets. We will use Mamdani fuzzy rule of "If x is A then y is B" is defined as a fuzzy relation as follows:

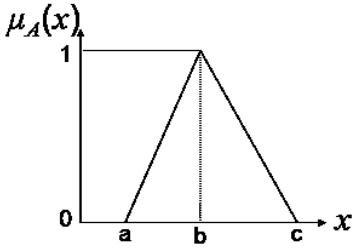
$\mu_R(x, y) = A(x) \wedge B(y)$;

Where the inference is obtained by $\mu_B(y) = \max(\min(\mu_A(x), \mu_R(x, y))$ by setting up the linguistic variables conditions using if-then rule.

- Rule 1: IF x_1 is A_1^1 and x_2 is A_2^1 THEN y^1 is B^1
- Rule 2: IF x_1 is A_1^2 or x_2 is A_2^2 THEN y^2 is B^2

Triangular Membership Function: Let A be a fuzzy set defined over a universe of discourse X and let c, a and b be real numbers such that a ≤ b ≤ c. The triangular membership function $\mu_A(x)$ is defined as:

$$\mu_A(x) = \begin{cases} 0 & \text{if } x \leq a \\ \frac{x-a}{b-a} & \text{if } a < x < b \\ 1 & \text{if } x = b \\ \frac{c-x}{c-b} & \text{if } b < x < c \\ 0 & \text{if } x \geq c \end{cases}$$



Membership functions will be defined for required input variables, which will help provide a framework for fuzzification [8]. One of the cases is the following membership functions:

a. Temperature Membership Functions

Wheat (Optimal: 15-20°C)

Low:

$$\boldsymbol{\mu_{\text{Low}}(\mathbf{T}) = \begin{cases} \mathbf{1} & \text{if } \mathbf{T \leq 15} \\ \frac{\mathbf{20 - T}}{\mathbf{5}} & \text{if } \mathbf{15 < T < 20} \\ \mathbf{0} & \text{if } \mathbf{T \geq 20} \end{cases}}$$

Moderate:

$$\mu_{\text{Moderate}}(\text{T}) = \begin{cases} 0 & \text{if T} \leq 15 \\ \frac{\text{T} - 15}{5} & \text{if } 15 < T < 20 \\ 1 & \text{if T} = 20 \\ \frac{25 - \text{T}}{5} & \text{if } 20 < T < 25 \\ 0 & \text{if T} \geq 25 \end{cases}$$

High:

$$\mu_{\text{High}}(\text{T}) = \begin{cases} 0 & \text{if T} \leq 20 \\ \frac{\text{T}-20}{5} & \text{if } 20 < T < 25 \\ 1 & \text{if T} \geq 25 \end{cases}$$

b. Rainfall Membership Functions

Wheat (Optimal: 400-600 mm/year)

Low:

$$\mu_{\text{Low}}(\text{R}) = \begin{cases} 1 & \text{if R} \leq 400 \\ \dfrac{600 - \text{R}}{200} & \text{if } 400 < R < 600 \\ 0 & \text{if R} \geq 600 \end{cases}$$

Moderate:

$$\mu_{\text{Moderate}}(\text{R}) = \begin{cases} 0 & \text{if R} \leq 400 \\ \dfrac{\text{R} - 400}{200} & \text{if } 400 < \text{R} < 600 \\ 1 & \text{if R} = 600 \\ \dfrac{800 - \text{R}}{200} & \text{if } 600 < \text{R} < 800 \\ 0 & \text{if R} \geq 800 \end{cases}$$

High:

$$\mu_{\text{High}}(\text{R}) = \begin{cases} 0 & \text{if R} \leq 600 \\ \dfrac{\text{R} - 600}{200} & \text{if } 600 < R < 800 \\ 1 & \text{if R} \geq 800 \end{cases}$$

c. Drought Membership Functions

Wheat (Average yield loss: 20%)

Low:

$$\mu_{\text{Low}}(\text{D}) = \begin{cases} 1 & \text{if D} \leq 10 \\ \dfrac{30 - \text{D}}{20} & \text{if } 10 < D < 30 \\ 0 & \text{if D} \geq 30 \end{cases}$$

Moderate:

$$\mu_{\text{Moderate}}(\text{D}) = \begin{cases} 0 & \text{if D} \leq 10 \\ \frac{\text{D}-10}{20} & \text{if } 10 < D < 30 \\ 1 & \text{if D} = 30 \quad \frac{50-\text{D}}{20} \quad \text{if } 30 < D < 50 \\ 0 & \text{if D} \geq 50 \end{cases}$$

High: $$\mu_{\text{High}}(\text{D}) = \begin{cases} 0 & \text{if D} \leq 30 \\ \frac{\text{D}-30}{20} & \text{if } 30 < D < 50 \\ 1 & \text{if D} \geq 50 \end{cases}$$

Rule based results

Rule 1: IF Temperature is Low AND Rainfall is High AND Drought is Low THEN Yield is 5.2 tons/ha.

Rule 2: IF Temperature is Medium AND Rainfall is Medium AND Drought is Moderate THEN Yield is 4.0 tons/ha.

Rule 3: IF Temperature is High AND Rainfall is Low AND Drought is High THEN Yield is 2.5 tons/ha

For the input values:

- Temperature: 22°C
- Rainfall: 350 mm/year
- Drought: 30%
- Activated Rule: Rule 2
- Minimum degree of fulfilment:
- Degree of Fulfillment $= \min(0.6, 0.5, 1) = 0.5$
- Output Contribution: Yield = 4.0 tons/ha with a weight of 0.5.

Comparison with Traditional Non-Fuzzy Approaches:

Traditional non-fuzzy approaches to analyzing the climate-poverty-hunger nexus rely on deterministic models with precise input data and fixed relationships between variables. These models are well-suited for linear systems with reliable data but struggle to handle uncertainty, data incompleteness and nonlinear interactions, which are common in real-world socio-economic and environmental systems.

In contrast, fuzzy approaches excel at modeling systems with inherent vagueness and imprecision by using linguistic variables and fuzzy rules. They can accommodate uncertain data and provide outputs in the form of ranges or degrees of membership, offering a more realistic representation of complex interactions. However, fuzzy models can be computationally intensive and more complex to interpret compared to traditional methods.

Despite their differences, both approaches have strengths; non-fuzzy models are simpler and more efficient for well-defined systems, while fuzzy models are more flexible and robust for uncertain, dynamic environments. Therefore, combining these methods can yield better insights and more reliable policy recommendations.

Aspect	Traditional Non-Fuzzy Approaches	Fuzzy Approaches
Handling of uncertainty	Poor – assumes precise inputs and outputs	Excellent – models uncertainty and vagueness directly
Suitability for Nonlinear Systems	Limited – often assumes linearity	High – inherently capable of modeling nonlinearity
Data Requirements	High – requires precise, complete data	Low – can work with imprecise, incomplete data
Output Type	Precise, single-value output	Ranges with degrees of membership
Flexibility	Low- Fixed structures and rules	High – adaptable by modifying rules and membership function

1. Validation against Historical Data

Identification of Key Historical Events: Use of well-documented historical events such as major droughts, floods, or economic crises, which have significant climate, poverty and hunger implications. Examples:

- The 1984 Ethiopian famine linked to severe drought.
- The 2008 global food crisis exacerbated by rising temperatures and economic shocks.
- The 2010 Pakistan floods affecting millions and leading to increased poverty and hunger levels.
- Source data from global databases like:
    - FAOSTAT for hunger statistics.
    - World Bank for poverty indices.
    - IPCC for climate data.

2. Validation with previous studies done:

- Study B: Singh & Sahu (2017), "Climate Sensitivity of Cereal Crops: Focus on Rice, Jowar and Soybean"
    - Focus: This study investigates how climate variability influences the growth of staple crops like Rice, Jowar and Soybean crops in Central India.

- Findings: The research indicates that Rice is highly sensitive to water stress, particularly in regions with irregular monsoon patterns. Jowar faces risks due to temperature rise, while Soybean is vulnerable to heat waves during flowering, significantly reducing yield.
- Comparison with this Study: This fuzzy logic model predicts similar outcomes, indicating that Rice will be negatively impacted by irregular rainfall and water stress, Jowar will face productivity declines due to high temperatures and Soybean will suffer from heat stress. The above agreement further supports this model's ability to predict the effects of climate change on these crops.

- Study C: Desai & Singh (2017), "Climate Change and Rural Poverty: Impact on Crops like Rice, Jowar and Soybean in India"

  - Focus: This study links climate change to rural poverty, particularly in states dependent on Rice, Jowar and Soybean cultivation.
  - Findings: Places like Maharashtra and Chhattisgarh, where crops like Jowar and Soybean are very important, are experiencing more poverty because crop yields are decreasing. This is happening because of extreme temperatures and unpredictable rainfall. Similarly, states like West Bengal and Odisha, which grow a lot of rice, are seeing lower crop yields. This is making food insecurity and poverty worse in these areas.
  - Comparison with this Study: This fuzzy logic model will also predict how SDG's are interlinked, like how poverty increases in these same regions due to crop failure from climate extremes. The model suggests that Jowar and Soybean yields are particularly degrading because of temperature rise and delayed rain, leading to economic losses and higher poverty levels. This is in support of the findings of researcher Desai & Singh where they demonstrated the model's ability to project poverty linked to crop declines.

- Study D: Kumar et al. (2018), "Assessing the Impact of Climate Change on Food Security: Focus on Jowar, Rice and Soybean"

  - Focus: This study assesses the food security implications of climate change for crops like Rice, Jowar and Soybean.
  - Findings: The research shows that Rice is highly susceptible to water scarcity and temperature spikes, especially in the Eastern states. Jowar is predicted to face a 25-30%

reduction in yield in the Deccan Plateau region due to higher temperatures, while Soybean yields could drop by 20% in Madhya Pradesh due to delayed rainfall.

- Comparison with this Study: This fuzzy model also predicts similar trends, with Rice showing reduced yields in Eastern India due to irregular rainfall, Jowar facing a decline due to temperature increase and Soybean suffering from delayed monsoons. The model's projections align with the findings of Kumar et al., confirming that climate change is a significant threat to food security for these crops.

- Study F: Santos & Ribeiro (2019), "Applications of Fuzzy Logic in Modeling Crop Yields under Climate Variability"

  - Focus: This study explores the use of fuzzy logic in predicting the impact of climate variability on crop yields for cereal crops.
  - Findings: The study shows that fuzzy logic models can capture the complex, non-linear relationships between climate factors and crop yields, making them effective tools for forecasting climate-induced risks for crops like Rice, Jowar and Soybean.
  - Comparison with this Study: This fuzzy logic model applies similar methodologies and finds that the climate-induced risks (such as temperature rise, water stress and irregular rainfall) will significantly affect Rice, Jowar and Soybean yields, validating the use of fuzzy logic in crop modeling.

Calibration Process

- Tuning Membership Functions: Adjust membership functions for input variables (e.g., low, medium, high poverty levels) to better fit historical data distributions.
  Example: A drought with a temperature anomaly of +2°C might shift membership function boundaries for "high temperature" in your model.
- Refining Fuzzy Rules: Update fuzzy rules based on discrepancies between observed and predicted outputs.
  Example: If a rule like "High temperature AND Low income → High hunger" under predicts hunger during a specific drought event, adjust the rule weight or parameters.

Result and analysis: Python Implementation: We developed a Python script that applies the rule base, computes the final yield prediction and performs fuzzification in order to expedite the computation process.

Temperature, rainfall and drought conditions are defined as membership functions in the fuzzy logic system used to determine wheat production. For instance, the term Medium, which is employed in the

criteria that specify the yield of 4.0 tons/ha, has a membership degree of 0.6 when the temperature is 22°C. Similar to yield prediction, this method can be used for sorghum and rice if the rules and membership functions are appropriately specified based on the crop's yields and conditions [19].

Expected Outcomes

1. Resource allocation with Fuzzy: Creating fuzzy model using pre assumed values and parameters that will help find potential future events and make well-informed choices for farmers to find better location, crop selection and hence work on financial loses and increased productivity. Improved efficiency in resource allocation (water, fertilizers, energy) in sustainable agricultural practices.

2. Crop Breeding with Fuzzy Logic: As data for crops becomes more accessible, this fuzzy logic model could help identify which genetic traits are most beneficial for specific environmental conditions. For example, if the model detects that crops with higher drought tolerance thrive in regions experiencing more frequent dry spells, breeding programs could focus on developing varieties with these traits.

3. Collaborations with AgriTech Companies: In the future, partnerships between this research and agri-tech companies that specialize in genetic modification could make these tools more accessible to both large-scale farms and smallholders. For instance, a seed company could use the fuzzy logic recommendations to offer genetically modified seeds that are more resilient to climate stressors, based on local conditions.

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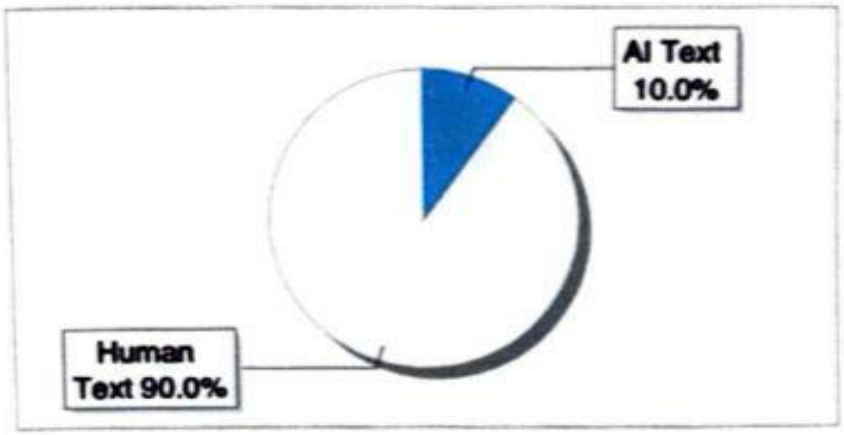

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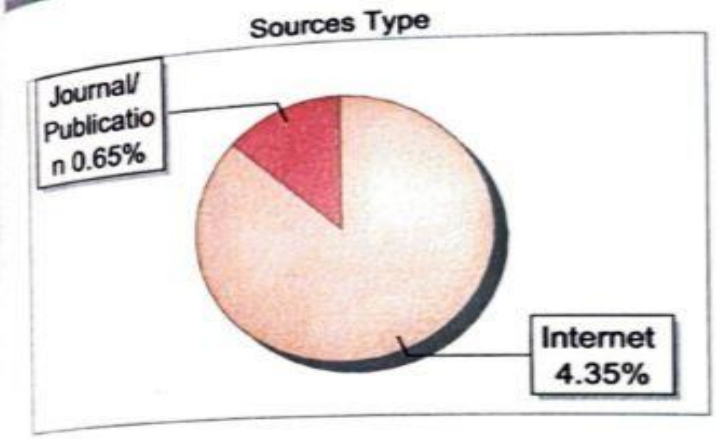

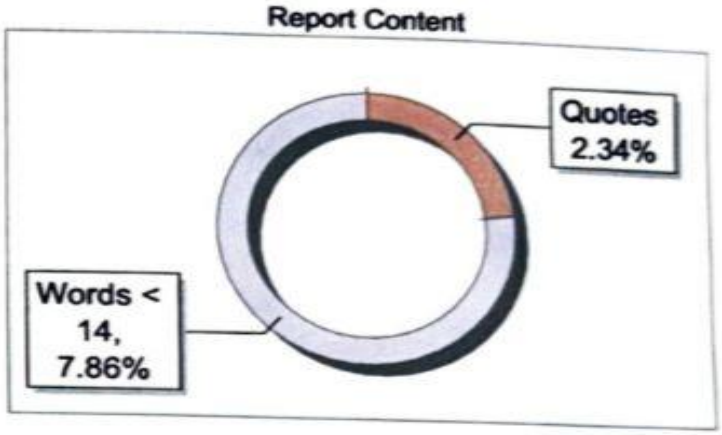

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